

Stirling Engine Development Using Virtual Prototyping

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Abstract. A successful realization of Stirling engines is conditioned by its correct conceptual design and optimal constructional and technological mode of all parts. Initial information should provide computation of real cycles of the engines. The information from base engine dimensions like piston bore or piston stroke. After that more sophisticated methods can be used for the development. The paper presents calculation models and results of dynamics and thermodynamic cycles of the external heat supply engines. High-level FE (Finite Element), MBS (Multi Body System) or CFD (Computational Fluid Dynamics) models arising from the description of real processes which run in an external heat supply engine are used for virtual prototype of 3 kW Stirling engine with Rhombic mechanism.

1 Introduction

A prototype of γ -modification Stirling engine with an electric plant with 500W power output has been realized in previous stages. Within the frame of this pilot project 1D computational models [1], [4], and subsequently 3D computational models of virtual prototype levels [2], [3] have been developed and applied.

These computational models are based on CFD in the case of thermodynamics and on MBS in the case of structural dynamics of Stirling engine. The computational models have been verified by experiments on the Stirling engine prototype.

The application of the virtual development on Stirling engine with rhombic mechanism (β -modification) for an electric plant up to 3000 W is the aim of the next stage. Figure 1 shows parts of the virtual development of the 3000W Stirling engine. A result of the virtual development is a prototype design of the engine with specified parameters.

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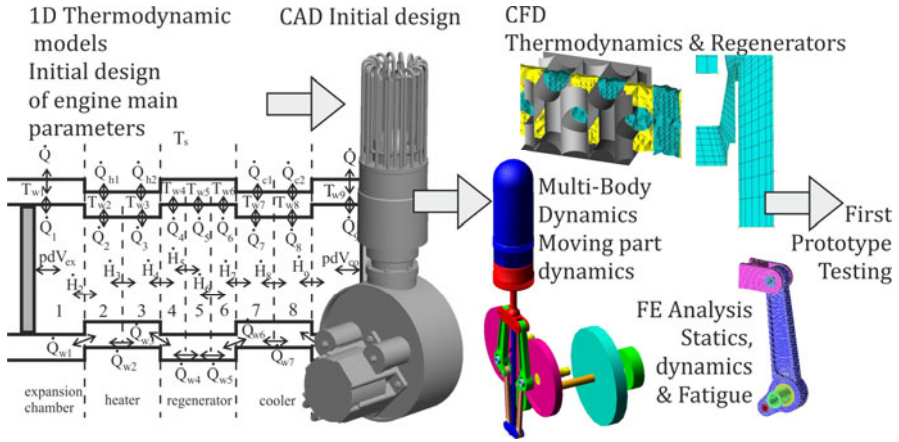


Fig. 1. Virtual development process of Stirling engine

2 Thermodynamic Cycles

In this particular case, the operating gas volume is sealed with fixed walls and two moving pistons. The engine consists of an expansion chamber, a heater, a regenerator, a cooler and a compression chamber. Individual chambers can be further split into a suitable number of zones. The volumes of the expansion and compression chambers change periodically with movements of the pistons. Temperatures, pressures and gas flow speeds in different zones can be assumed as constant for now or can be approximated between the zone limits using a linear or another suitable function [1].

In particular energy transport members include the volume work of both pistons, heat flows between the engine walls and the operating gas, enthalpy flows through the limits of the nine zones, heat flows through the walls separating different chambers and the heat flows between the engine walls and the ambient room [1].

Balance equations for the mass, energy and momentum can be designed for a generalised Stirling engine volume element. The following one-dimensional balance applies for this volume element:

Mass:

$$\frac{dm}{dt} = \dot{m}_i - \dot{m}_j \quad . \quad (1)$$

Energy:

$$\frac{dU}{dt} + \frac{1}{2} \frac{d(mw^2)}{dt} = \dot{m}_i \left(h_i + \frac{1}{2} w_i^2 \right) - \dot{m}_j \left(h_j + \frac{1}{2} w_j^2 \right) + \dot{Q} + P \quad . \quad (2)$$

Momentum:

$$\frac{d(mw)}{dt} = \dot{m}_i w_i - \dot{m}_j w_j + \sum F \quad , \quad (3)$$

The w symbol presents velocity, t is time, $\dot{Q}$ is heat flow, P is power, U is internal energy and F means force. Forces in the equation (3) are pressure forces and friction forces, which affect the operating gas in the generalised volume.

The following applies for the power P led in/out in the equation (2):

$$P = p\dot{V} = p \frac{dV}{dt} \quad , \quad (4)$$

Where V , T and r are volume, temperature and gas constant respectively. Together with the status equation for the ideal gas,

$$pV = mrT \quad , \quad (5)$$

these equations form a single-dimensional computational model of flows inside the Stirling engine.

The above set of differential equations must be supplemented with additional computational models for:

- calculation of pressure losses in the Stirling engine,
- calculation of heat transfer in the Stirling engine,
- calculation of Stirling engine operating chamber volume changes.

3 Optimizing of Driving Mechanism

A rhombic driving mechanism has been applied for the proposed Stirling engine. While the issue of the dynamic balance of the driving mechanisms has been well elaborated and is based on the fact that both the geometrical and mass parameters of individual cylinder units are identical in internal combustion engines, these prerequisites are usually not met in case of the Stirling engine.

MBS can be applied as effective tools for solving Stirling engine dynamics. Multi-body systems enable solving different dynamic issues of complex systems combining rigid and flexible bodies. In the case of Stirling engine mechanisms, they can be used to find the optimum alternative for balancing the driving mechanism [1].

In general, the driving mechanism transfers forces to attachments. These forces should be as minimal as possible. Therefore, the reaction force is selected as a target function. A balance weight static moment and an angular position of balance weight are used as parameters for optimization. Figure 2 presents results of a design process and determines global minimum of driving mechanism reaction force.

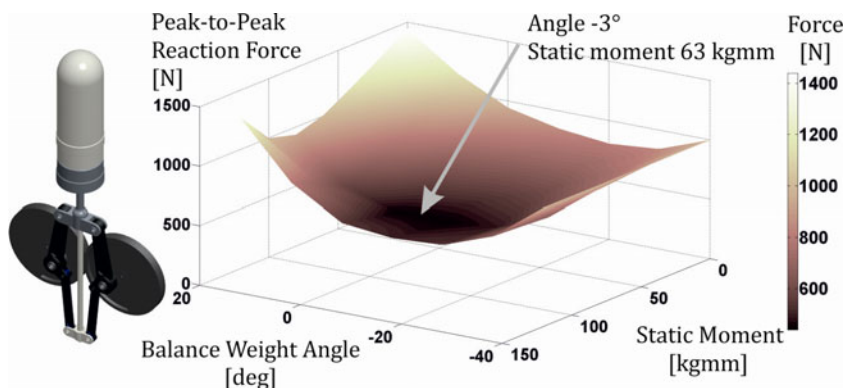


Fig. 2. Design results of driving mechanism balance weights

4 Dynamic Solution of Driving Mechanism

Driving mechanism dynamics considering loadings (e.g. combustion pressure forces) is also solved in MBS. Body deformations, velocities and accelerations and forces between different bodies are results of the MBS calculation model.

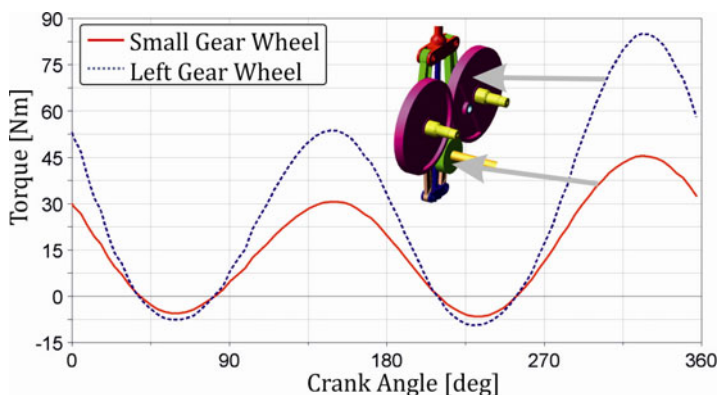


Fig. 3. Computed gear wheel torques

The engine speed of 1500 rpm is chosen for the central shaft. Practically, the values of the actual engine speed of the central shaft vary about this value in dependency on body inertia moments and torsional stiffness of some parts.

Stirling engine concept uses mainly roller bearings for interaction between the components. Slide bearing are used only for small connection rod bearings. Loadings of the bearings or gear wheels (reaction forces vs. crank angle) are determined from MBS calculation results and used for the design of the bearings. Figure 3 presents the calculated torque of a left gear wheel and a small gear wheel placed on the central shaft.

5 Conclusions

The virtual prototypes based on CFD, MBS and FEM enable to speed up the development process of new Stirling engine solutions significantly. Simultaneously they enable to decrease the costs required for the production of expensive prototypes. The documentation for production of Stirling engine components is produced on the basis of numeric simulations.

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